



HAL
open science

Mucus and ciliated cells of human lung: splitting strategies for particle methods and 3D stokes flows

Robin Chatelin, Philippe Poncet, Alain Didier, Marlène Murriss-Espin,
Dominique Anne-Archard, Marc Thiriet

► To cite this version:

Robin Chatelin, Philippe Poncet, Alain Didier, Marlène Murriss-Espin, Dominique Anne-Archard, et al.. Mucus and ciliated cells of human lung: splitting strategies for particle methods and 3D stokes flows. IUTAM Symposium on Particle Methods in Fluid Mechanics, Oct 2012, Lingby, Denmark. pp.0. hal-04023026

HAL Id: hal-04023026

<https://hal.science/hal-04023026v1>

Submitted on 10 Mar 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Open Archive TOULOUSE Archive Ouverte (OATAO)

OATAO is an open access repository that collects the work of Toulouse researchers and makes it freely available over the web where possible.

This is an author-deposited version published in : <http://oatao.univ-toulouse.fr/>
Eprints ID : 10294

To cite this version :

Chatelin, Robin and Poncet, Philippe and Didier, Alain and Murrise-Espin, Marlène and Anne-Archard, Dominique and Thiriet, Marc
Mucus and ciliated cells of human lung : splitting strategies for particle methods and 3D stokes flows. (2012) In: IUTAM Symposium on Particle Methods in Fluid Mechanics, 15 October 2012 - 17 October 2012 (Lingby, Denmark). (Unpublished)

Any correspondence concerning this service should be sent to the repository administrator: staff-oatao@listes-diff.inp-toulouse.fr

Mucus and ciliated cells of human lung : splitting strategies for particle methods and 3D stokes flows

R. Chatelin[†], P. Poncet^{†*}, A. Didier[‡], M. Murriss-Espin[‡], D. Anne-Archard[§], M. Thiriet[◇]

[†]Toulouse Institute of Mathematics, UMR CNRS 5219, 135 av. de Rangueil, F-31077 Toulouse.

[‡]CHU Larrey Toulouse, 24 ch. de Pourville, TSA 30030, F-31059 Toulouse.

[§]IMFT, UMR CNRS-INP-UPS 5502, 2 allée du Professeur Camille Soula, F-310400 Toulouse.

[◇]Lab. J-L. Lions, CNRS UMR 7598, UPMC Paris VI, BC 187, 4 place Jussieu, F-75252 Paris.

Keywords: Particle methods, Transport, 3D Stokes equations, Complex geometries, Biological flows.

ABSTRACT

Lung walls are covered by a film of mucus, whose motility is fundamental for a healthy behavior. Indeed, mucus traps inhaled aerosols (bacteria, dust, ...), and moves from smallest to largest airways, until it reaches esophagus where it is swallowed or expectorated. A lot of biological parameters are responsible for mucus motion [6], such as the vibrations of ciliated cells covering lung walls (cilia height, frequency, ...), mucus/air interaction, water saturation in mucin network, mucus thickness, ...

A change in these biological parameters can lead to dramatic dysfunction of mucus, usually leading to insufficient motility. One of our focuses is cystic fibrosis, which results in an increased mucus viscosity, leading to bacteria proliferation and severe pathologies [1]. Another example is ciliotoxic inhalation, such as nicotine, leading to stop the beating of ciliated epithelium. The numerical simulation allows to split apart different phenomena and to investigate which one is dominant, depending on the biological configuration considered.

The present work focuses on numerical strategies to compute mucus flow around a ciliated epithelium cell (see figure 1). We consider a variable viscosity flow around a complex moving geometry. The Reynolds number $Re \simeq 10^{-8}$ is very small and governing equations of momentum are reduced to the quasi-static Stokes problem. Viscosity and density are spatially variable and satisfy the same transport equation depending on mucus velocity, itself satisfying the 3D Stokes equation depending of viscosity.

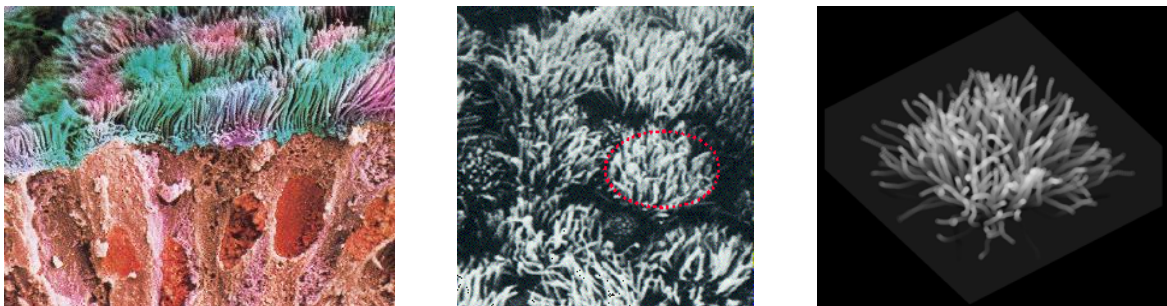


Figure 1: Views of respiratory epithelial cells (to the left and to the middle, red dots show a cell delimitation) and ciliated cells used in numerical simulation (to the right).

Here we consider a computational box Q split into a body denoted $B(t)$ containing the epithelial cell, and a fluid domain denoted $\Omega(t) = Q \setminus \overline{B(t)}$. In body $B(t)$, velocity is imposed $u = \bar{u}$ by a penalization method. The cilia velocity \bar{u} follows a first order hyperbolic equation taking into account the actin polymerization process of beating (model of elastic beams of variable modulus). This sets up a one-way coupling between cells and fluid.

Given these assumptions the fluid equations in complex and moving geometry are

$$\partial_t \mu + u \cdot \nabla \mu = 0 \quad \text{in } Q \quad (1)$$

$$-\operatorname{div}(\tau) + \nabla p + \frac{\chi(t)}{\varepsilon}(u - \bar{u}) = f \quad \text{and} \quad \operatorname{div} u = 0 \quad \text{in } Q \quad (2)$$

$$u(x, t) = 0 \quad \text{or} \quad \partial_n u(x, t) = 0 \quad \text{on } \partial Q \quad (3)$$

where $\chi(t)$ is the characteristic function of body $B(t)$, and $\tau = \mu(\nabla u + \nabla u^T)$ the strain rate tensor. At a Mathematical level, this is a non-linear coupling between second-order elliptic and first order hyperbolic partial differential equations.

As transport phenomena are dominant, a particle method is used to solve equation (1) using grid-particle formulation. Velocity follows the 3D Stokes equation (2) and is computed on staggered grids, on which geometry is penalized (such as in [2]). Interpolated between grid and particles by means of Monaghan's M_4' kernel. To the opposite of moderate or high Reynolds number flows, effect of boundary conditions (3) are not localized in the wall neighborhood [4] and panel methods are not efficient: a fixed point based on a divergence free projection is then used [3] to satisfy boundary conditions.

One can rewrite the diffusion term as $\mu^{-1} \operatorname{div} \tau = -\Delta u + \tau \nabla \ln \mu$ which allows to solve equation (2) by means of an iterative process involving only Poisson equations, and thus allowing the use of fast second and fourth-order elliptic solvers. These standard PDEs are fast to solve and also avoid to store matrix coefficients, in the same philosophy as most modern particle or vortex methods.

Future work will use heavily this computational method in order to identify biological behavior by means of neural networks, with a machine learning performed in the same spirit as [5].

References

- [1] T. Damy, P-R. Burgel, J-L. Pepin, P-Y. Boelle, C. Cracowski, M. Murriss-Espin, R. Nove-Josserand, N. Stremler, T. Simon, S. Adnot, B. Fauroux, Pulmonary acceleration time to optimize the timing of lung transplant in cystic fibrosis, *Pulmonary Circulation* 2:1 (2012), 75–83.
- [2] M. El Ossmani and P. Poncet, Efficiency of multiscale hybrid grid-particle vortex methods, *SIAM MMS* 8:5 (2010), 1671–1690.
- [3] J.L. Guermond, P. Mineev, J. Shen, An overview of projection methods for incompressible flows, *Comp. Meth. Appl. Mech. Eng.* 195, 6011–6045 (2006).
- [4] P. Poncet, Analysis of direct three-dimensional parabolic panel methods, *SIAM J. Numer. Anal.* 45:6 (2007), 2259–2297.
- [5] P. Poncet, R. Hildebrand, G-H. Cottet, P. Koumoutsakos, Spatially distributed control for optimal drag reduction in cylinder wakes, *J. Fluid Mech.* 599 (2008), 111–120.
- [6] M. Thiriet, Tissue Functioning and Remodeling in the Circulatory and Ventilatory Systems (Vol. 5), Series Biomathematical and Biomechanical Modeling of the Circulatory and Ventilatory Systems, Springer, New York, 2012.